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A COMPARISON OF THE ACTUAL AND PREDICTED PERFORMANCE OF A SOLAR--ETC(U)
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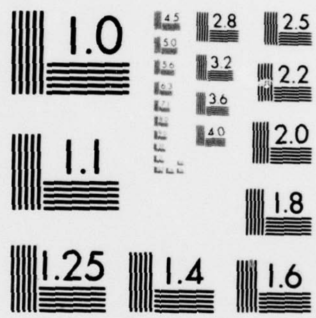
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LEVEL II

(6) A COMPARISON OF THE
ACTUAL AND PREDICTED PERFORMANCE OF
A SOLAR ASSISTED SPACE HEATING SYSTEM

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I Introduction

Recent increases in fuel prices have resulted in an interest in the development of alternate sources of energy. Solar energy is one such source, as the technical feasibility of heating buildings using flat-plat collectors has been established both in theory and in practice. While the construction phase of solar energy systems requires little more skill than is needed to install conventional heating systems, the design phase is considerably more complex. The fact that solar energy is often not available when it is needed makes system design unconventional in that the sun supplies some, but not all, of the building energy requirement. In addition, an auxiliary source of energy, capable of meeting the peak demand, must be provided to supply heat whenever energy from the sun is not available.

In the past, because of the uncontrolled nature of solar energy, extensive and costly computer studies (taking into account hourly weather data from the site in question) have been required to design and evaluate solar energy systems. For the purposes of determining system feasibility, the cost of these studies can be prohibitive. Thus, there is need for a simple, manual method for making the necessary design calculations and system performance evaluations

prior to a computer analysis. It is the purpose of this paper to describe such a method, and to compare the predictions of the method to the actual performance of a solar facility. Section II of this paper gives a brief description of this manual method, while Section III describes the solar facility from which data was collected. Sections IV and V summarize the system monthly and component performance, respectively. Conclusions follow in Section VI.

II The Universal Curve for Solar Heating

In the course of the development of a solar energy system computer model for use in CERL's Building Load Analysis and System Thermodynamics (BLAST) energy analysis program, CERL performed several hundred hour-by-hour simulations of solar systems used with typical Army buildings in various parts of the country. (1) Analysis of the performance of these systems indicated that, with proper normalization, the performance of a given solar system for all buildings in all locations could be represented for the purposes of feasibility analysis by a single universal performance curve.

A schematic of the type of system under consideration is given in Figure 1. Solar radiation, when available, is converted to thermal energy at the collectors and is transferred to the storage tank by the collector and storage pumps. The heat exchanger, isolating the collection and storage loops, allows the collector fluid to be freezed-protected. Normal operation of the system permits heating of the storage tank whenever sufficient solar energy is available.

Energy is taken from the tank by the load pump (if the storage water is sufficiently hot) whenever there is a demand for heat in the building. If the storage temperature falls too low for heating (,95°F), the auto-valve diverts flow around the tank, and the auxiliary heater is energized. As pictured, this system is representative of a large class of liquid solar energy system; all the solar heating simulations run for this study assumed such a configuration.

Use of the universal curve for solar heating, pictured in Figure 2, allows an estimation of the monthly (and seasonal) performance of the system of Figure 1. In order to apply the curve, the user must input only two quantities, the monthly radiation incident on the proposed collector array, and the monthly thermal energy requirement of

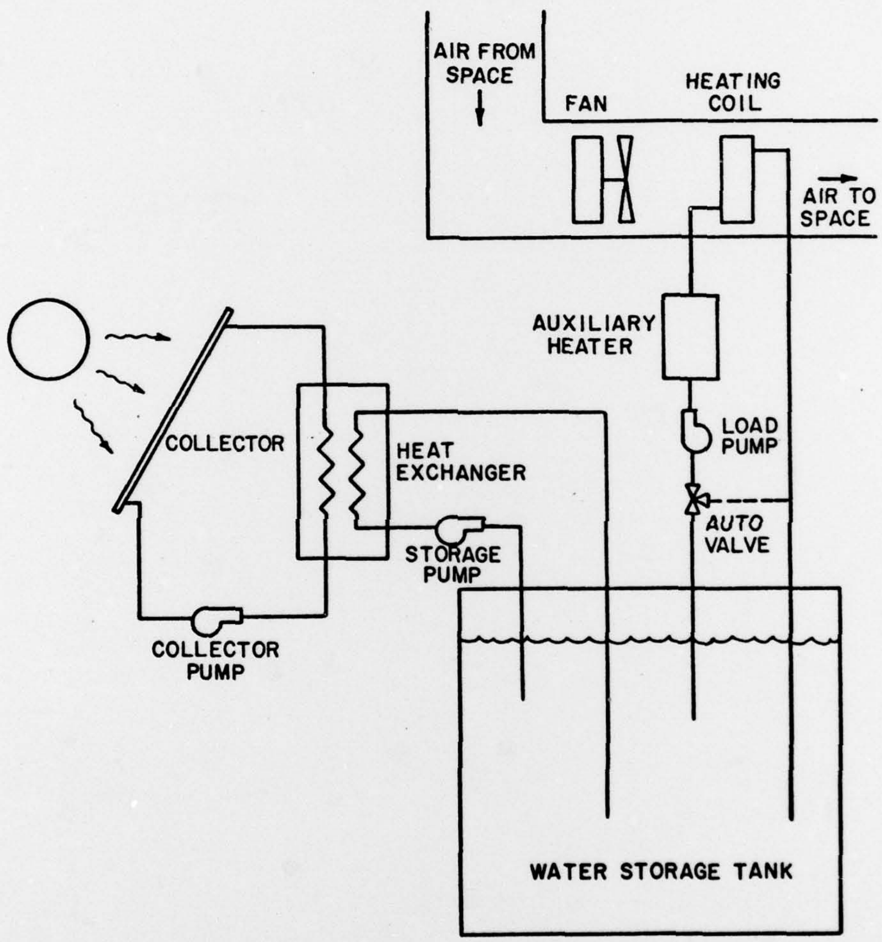

FIGURE 1
CERL SOLAR HOUSE
(SCHEMATIC)

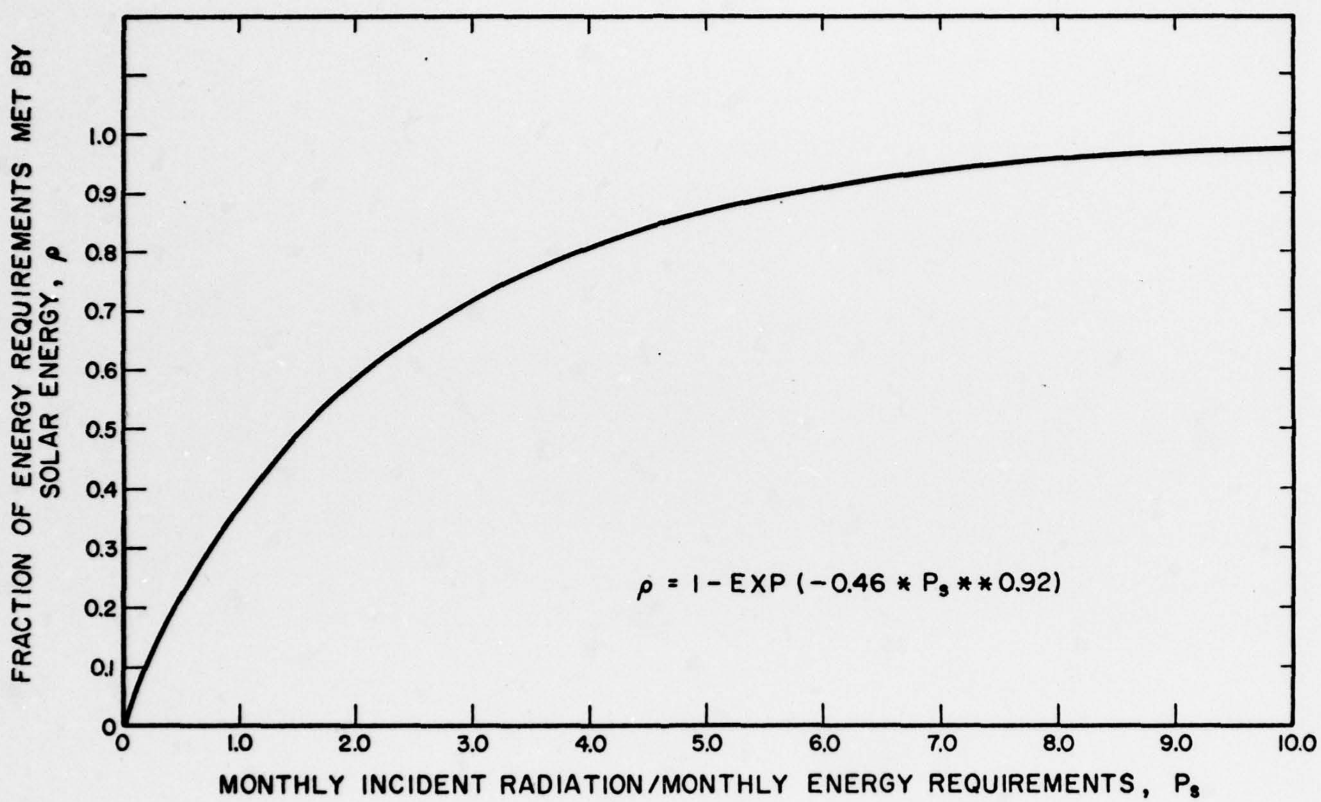

FIGURE 2
THE UNIVERSAL CURVE FOR SOLAR SPACE HEATING

the building in question. The ratio of these two quantities, defined to be the solar system performance parameter, P_s, is a relative measure of the amount of available solar energy compared to the thermal energy requirement of the building. Once P_s is computed, the curve may be consulted directly to estimate the fraction, ρ, of the building energy requirement which can be provided by the sun. As derived, it is the function of the universal curve to allow prediction of the monthly solar system performance for any value of P_s. A more detailed description of the curve (including curves for domestic heat water and solar heating and cooling applications) is given in Reference 2.

It can be seen from Figure 2, that the universal curve approach to solar system design offers a great advantage over an hour by hour computer analysis. Reasonable values of collector efficiency, heat exchanger effectiveness, and storage tank heat loss were assumed in the simulations which produced the universal curve. The fact that reasonable values for these parameters are contained implicitly within the curve greatly minimizes the amount of input information required of the user.

III A Description of the CERL Solar House

Data from CERL's solar house was used to evaluate the accuracy of the universal curve. This solar house is a 540 sq.ft. residence which has been retrofit with a solar heating system. Originally built to test a foam block construction concept, the structure consists of polystyrene blocks 6 inches thick by 12 inches high, and 8 to 10 feet in length. Structural integrity is provided by 3 inch poured concrete pillars spaced on two foot centers in holes in the blocks. Because of the thickness of the polystyrene, the thermal losses of the structure are due almost entirely to infiltration.

The solar system itself (Figure 1) is driven by an array of 12 single glaze, selective surface flat-plate collectors. An inhibited water-glycol solution is circulated through the array such that each collector is subject to approximately .63gpm when the collector pump is active. The collector loop, which contains approximately 12 gallons, is isolated from a pure water storage system by a single pass, counter flow heat exchanger.

The storage tank is a 1584 gallon precast concrete septic tank which has been foamed with 8 inches of polyurethene insulation and partially buried on the north side of the house. Two self priming pumps draw water from the tank; one (the storage pump) delivering water to the heat exchanger, the other (the load pump) to the heating coil. If, during the heating season, the storage temperature drops below 95°F, a 12KW electric "in line" heater supplies the auxiliary. energy. The auto diverting valve allows heat to be delivered to the coil, while by-passing the tank, when the backup is required.

The control of energy flows within the house is entirely automatic. Collection of solar energy is initiated whenever the collector plate is 10°F warmer than the tank, and is terminated when the collector is within 3°F of the tank temperature. Distribution of the heat to the building is controlled by a room thermostat, in conjunction with a commercially available aquastat (used to determine whether or not the tank is above the 95°F cut-off temperature). When solar energy is available, a demand for heat by the thermostat activates the load pump and distribution fan. As the tank falls below 95°F, the position of the auto-valve is changed (so that the resistance heat is delivered to the heating coil), and the auxiliary heater energized. In this case, the load pump and fan are still in operation.

The house is fully instrumented. A 40 channel data acquisition system records hourly values of solar radiation, fluid flow rates, liquid and air temperatures and energy flows within the system. The performance of the facility for a "typical" sunny winter (20°F) day is given in Figure 3. The instantaneous solar radiation, indicated by the circles on the figure, serves to add energy to the tank hourly in the amount shown by the squares. This energy increases the tank temperature (with no energy withdrawn) as given by the trianglular plot. Finally, the electrical energy expended by the pumps in collecting the solar energy is also shown, and is seen to be roughly 10% of the energy collected.

IV The Solar System Seasonal Performance

The monthly performance of the CERL solar house was tabulated for February, March, and April of 1977. A summary of the character of the 1977 heating season for these months is given in Table I.

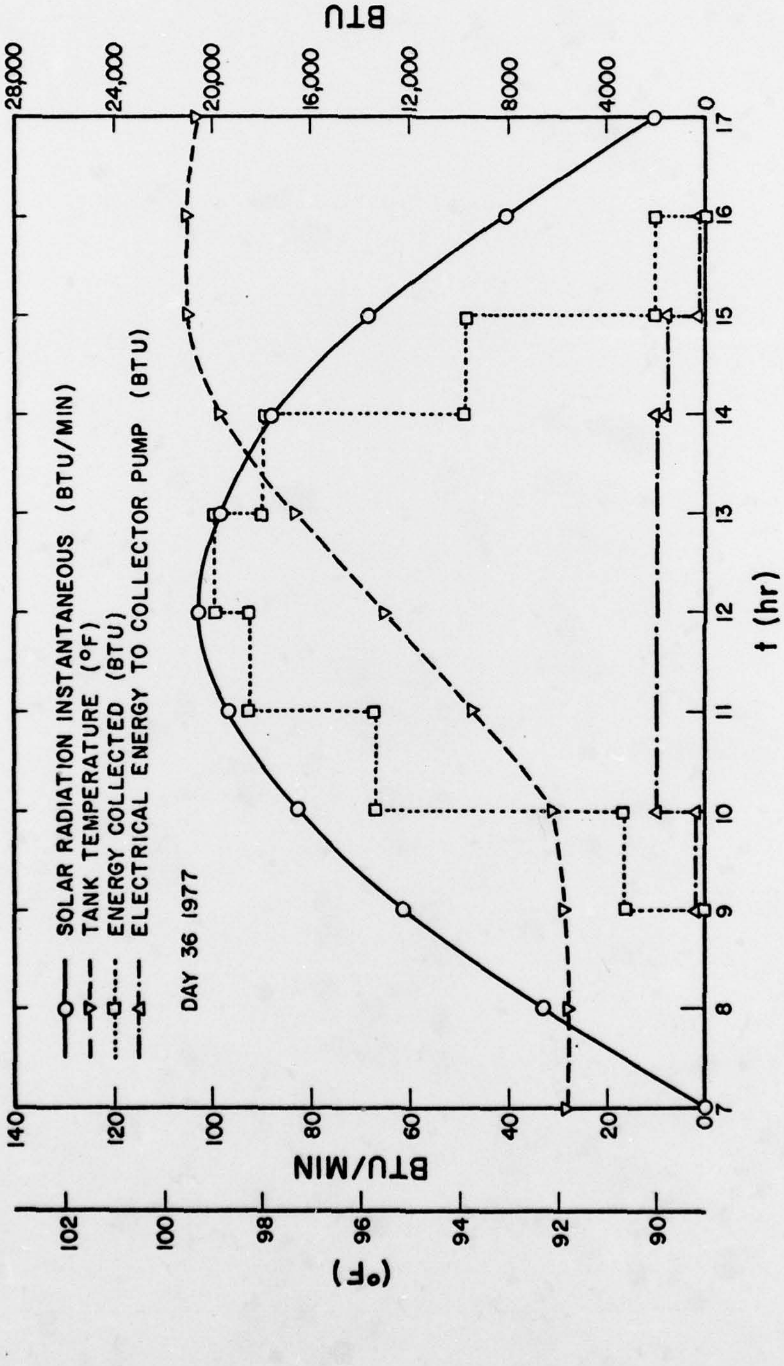

FIGURE 3
TYPICAL SUNNY WINTER DAY SOLAR SYSTEM PERFORMANCE

From the table it is seen that, for the months under consideration, the temperature was generally higher than normal, while the solar radiation was slightly lower.

TABLE I

Temperature (°F)	FEB	MAR	APR
Monthly Mean ([illegible])	28.6	45.1	57.7
Departure from normal (3)	-.5	+5.7	+6.4
Horizontal Solar Radiation (Btu/ft^2)	**FEB**	**MAR**	**APR**
Monthly Mean (1977)	773	929	1299
Departure from normal (4)	-97	-251	-231

Both quantities required for a computation of P_s were measured directly. The solar radiation was determined by a pyranometer oriented in the plane of the collectors; instantaneous values of this quantity were integrated each hour and summed for the month. The total building load was measured by integrating an $\dot{m}Cp\Delta T$ product of the water delivered to the heating coil (where $\dot{m}$ is the mass flow rate, Cp the fluid specific heat, and ΔT the temperature differential across the coil) and summing this product for the month. The ratio of the solar radiation incident on the collector array to the building thermal energy requirement for each month gave a monthly value for P_s.

Measurement of the fraction, ρ, of the building energy supplied by the sun, was enabled by integrating an $\dot{m}\ Cp\Delta T$ product only when the energy delivered to the heating coil originated from the tank. The ratio of this product to the total load gives the actual percent solar directly.

A comparison of the measured and predicted ρ is given in Table II for each month.

TABLE II

Month (1977)	Slope Radiation ($BTUX10^6$)	Load ($BTUX10^6$)	P_s	ρ actual	ρ pred
FEB	6.3	4.2	1.5	.36	.41
MAR	6.9	3.0	2.3	.44	.58
APR	5.1	1.6	3.3	.71	.76

Here, ρ predicted is calculated from the universal curve using the measured value of P_s. For example, in February it is seen that $6.3X10^6$ Btu were incident upon the collector array. The thermal energy requirement for this time period was measured at the heating coil to be $4.2X10^6$ BTU. The ratio of these quantities gives a P_s of 1.5, which from the universal curve implies a ρ of .41. The actual measurement, however, indicated that the system operated at 36% solar (or ρ = .36).

The general trend in the data is quite evident; the system performance is always lower that expected. Possible reasons for this discrepancy are discussed in Section V.

V Solar System Component Performance

The deviation in ρ measured from ρ predicted led to a more detailed analysis of the solar system component performance, where the three principle components of the solar system are the heat exchanger, the storage tank and the collectors. Data from the performance of these components was compared to the models used in the generation of the universal curve.

In the derivation of the universal curve for solar heating, a heat exchanger effectiveness of .8 was assumed. An experimental determination of this quantity, is difficult to make because of the small temperature differentials which are present. From measurements of fluid flow rates, specific heats, and temperatures at the inlet and outlets of the primary and secondary sides of the heat exchanger it was found that the heat exchanger effectiveness for the test facility was greater than .8. Since it is shown in Reference 2 that, in this range, the heat exchanger effectiveness has little effect on solar system performance, it was concluded that the heat exchanger

was not causing the discrepancy between the actual and predicted values of ρ.

Heat losses from the storage tank were also examined. Measurements of the tank temperature as a function of time during periods for which energy was neither added to nor removed from the tank indicated that the rate of heat loss from the storage tank was in good agreement with the predictions of the model. (At CERL the decay of tank temperature with time was on the order of $.1^{o}F/hr$ under conditions of no energy flow for tanks at $100^{o}F$.) Furthermore, independent simulations have shown, that the monthly solar fraction, once again, is not strongly dependent on the rate of heat loss from the tank. According to the model, for a P_s of 2, tank U-values of .05 and .2 $BTU/ft^2\text{-}hr\text{-}^{o}F$ lead to solar fractions of .58 and .56 respectively. This result implies that the tank loss parameter is not responsible for the discrepancy between the measured and predicted monthly solar percent.

The final component to evaluate is the solar collectors. The National Bureau of Standards has defined a procedure for reporting the thermal performance of a solar collector. (5) The results of the test, plotted (open circles) in the N.B.S. format, are given in Figure 4 for a single collector of the type in use at CERL. Here, η is the instantaneous collecter efficiency, (defined to be the ratio of thermal energy collected to incident solar energy), $\overline{T_F}$ the average collector plate temperature, T_A the ambient temperature, and I the instantaneous solar radiation flux. From the figure it is seen that, in spite of the complexity of the collection process, the performance of a solar collector can be described to good approximation by only two parameters, namely the slope and intercept of an N.B.S. plot.

The NBS model for solar collector performance used in the development of the universal curve is shown (dotted line) in Figure 4. This line does not coincide with the actual single collector curve for the CERL collector NBS because the solar system simulations were performed before the performance data for the CERL collectors was available. The discreet data points on the figure show the CERL measurements of the actual performance of the CERL collector array for the dates shown. The general trend in the data is clear; the actual array performance falls short both of the single collector test results and of the line used to generate the universal curve. It is the discrepancy which accounts for a majority of the deviation in ρ_{actual} from $\rho_{predicted}$.

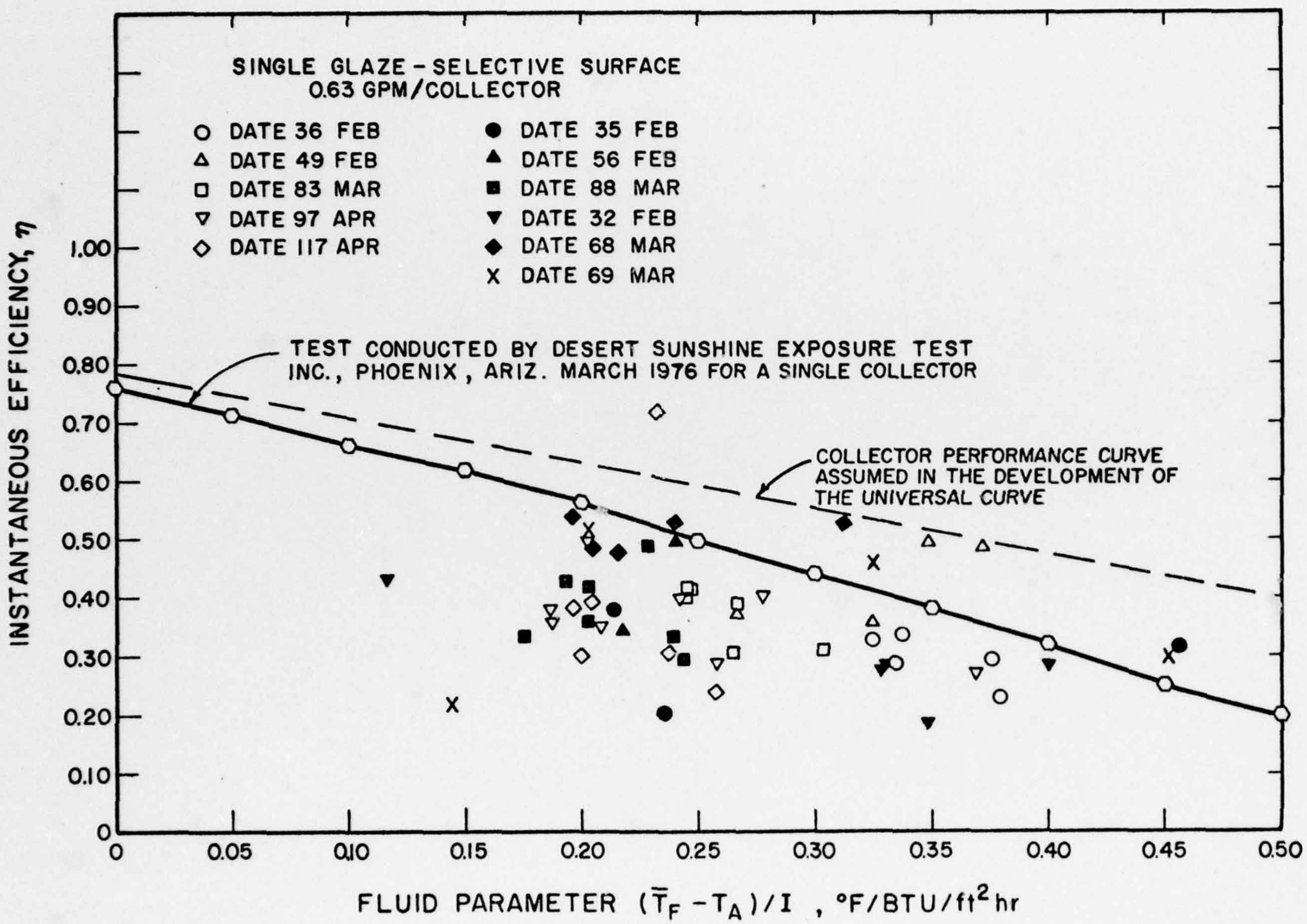

FIGURE 4
ACTUAL COLLECTOR ARRAY PERFORMANCE

While the reason for this degradation of collector array performance is currently under investigation, some comments can be made at this time. The actual collector array is subject to a range of climatic conditions, some of which were not present for the single collector measurement. In particular, collection efficiency is reduced during periods of high winds. Unfortunately, effects of this nature are difficult to estimate quantitatively as a model is required for the "local" wind in the vicinity of the collector.

Other factors exist which complicate the comparison of single collector to array performance. Heat loss in the headers, for example, minimal for a single collector, can be more significant in an array. Furthermore, any effects of long term degradation in plate absorptivity-emissivity or insulation thermal conductivity are not observed during a short duration N.B.S. test.

VI Conclusions

An analysis of the performance of a residential solar heating system was carried out for three months from the 1977 heating season and compared to the performance predicted using the universal curve. The measured solar fraction of energy supplied to the building was found to be less than predicted, but the reduced solar performance was explained, in part, by the fact that the CERL collector array efficiency was consistently lower than the published test results for a single collector. Therefore, in spite of the discrepancy between the actual and predicted percent solar, it is felt that the procedure for solar design offered by the universal curve provides the user with a simple, manual method for making an estimate of the feasibility of a solar heating system.

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